

Atomic and Bond Properties in Functionalized Esters and Amides

ANA M. GRAÑA, RICARDO A. MOSQUERA

Departamento de Química Física e Química Orgánica, Faculdade de Ciencias, Universidade de Vigo, Lagoas-Marcosende, E-36200 Vigo, Spain

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ABSTRACT: The properties of various atomic groups of molecules containing a carbonyl unit ($XCOY$) consisting of an ester ($Y = OR$) or amide function ($Y = NHR$) in different molecular environments ($X = H, Me, Et, OH, OMe, NH_2, NHMe, F, Cl$), as well as their influence on the properties of the alkyl chain ($R = C_8H_{17}$) in the molecule, were analyzed by use of the theory of atoms in molecules (AIM). To this end, the main atomic and bond properties for each atom in 18 carbonyl compounds of the aforementioned types were determined on the basis of $6-31++G^{**}/6-31G^*$ wave functions. The properties of the C and O atoms in the carbonyl group, and those of their bonds, are directly related to the nature and electronegativity of the X substituent and to the character of the Y group. The nature of the C—Y bond and the properties of the Y group are also dependent on the proximity of the X group. Based on the precision with which integrated properties were determined, assessed by $L(\Omega)$, the properties of the methylene groups of the R chain located in α and β with respect to Y are essentially dependent on the nature of Y and, to a lesser extent, on that of X. The methylene group in γ with respect to Y exhibits a dependence on the nature of the latter that vanishes in more distinct groups; therefore, the methylene in ε can be assimilated to one in an alkane. © 1999 John Wiley & Sons, Inc. *J Comput Chem* 20: 1444–1454, 1999

Keywords: AIM theory; electron density; bond properties; atomic properties; carbonyl group

Correspondence to: A. M. Graña; e-mail: uvipagr@uvigo.es

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Introduction

The theory of atoms in molecules (AIM)^{1,2} allows one to split a molecule in a rigorous manner, into disjoint subsystems complying with quantum-mechanical theorems and which can be readily identified with the constituent atoms. The ensuing subsystems lend themselves readily to quantification of any of their properties and allow those of the overall system to be estimated by adding up the individual values for the constituent fragments.¹⁻³

When a given set of such atoms exhibits constant properties and relative spatial arrangements in a series of molecules, a functional group is said to be present.³ In this manner, the AIM theory has accurately established the physical origin of the classification of chemical observations in terms of properties associated with functional groups. Although absolute transferability of the properties has proved to be an unreachable goal,⁴ nonsignificant practical differences can be obtained within the bounds of experimental error or even those of the precision achieved in their numerical computation.⁵ In previous work, the physical foundation of transferability between CH₃ and CH₂ fragments in unbranched linear alkanes was demonstrated via their bond⁶ and atomic properties.⁷⁻¹² This theory has even enabled the distinction between CH₂ groups in α with respect to a CH₃ group and the other CH₂ groups,⁹ and distinction among the carbonyl group in aldehydes, methylketones, and dialkylketones.

This work aimed at expanding the description of carbonyl compounds based on the AIM theory, which was started in previous work and involves the analysis of transferability of atom groups in carbonyls bonded to hydrogen or alkyl groups,⁵ the effect of an α substituent on the C=O unit,¹⁵ variability in the properties of the carbonyl oxygen with two α substituents (X, Y),¹⁶ the origin of the rotational barrier in amides and esters containing no additional heteroatom,¹⁷ and the hydrolysis of formamide.^{18,19} The main goals of the presented work were: (a) to establish quantitative relationships between the properties of the distributed carbonyl group ($XCOY$) and those of π -electron-releasing groups^{15,20}; (b) to study the influence of the different $XCOY$ units on the properties of the neighboring CH₂ fragments as a function of their relative position to the CO group and the nature of

the X and Y substituents; and (c) to analyze where the influence of the $XCOY$ unit on the alkyl chain ends and, consequently, where a methylene group can be considered equal to one of an n -alkane. For this purpose, a series of 18 different compounds including 9 esters ($Y = OR$) and 9 amides ($Y = NHR$), bearing various types of substituents ($X = H, Me, Et, OH, OMe, NH_2, NHMe, F$, and Cl), was studied. The alkyl chain was provided by an n -octyl group in all instances (Table I).

Description of Calculations

Atomic and bond properties were determined using the AIMPAC software package.²¹ Taking into account the size of the systems and the small influence of the computational level on changes in the atomic and bond properties provided by the AIM theory,²² we used 6-31++G**²³ wave functions for fully optimized geometries at the 6-31G* level.²⁴ The functions were computed by the programs GAUSSIAN-92²⁵ and GAUSSIAN-94.²⁶ Only the conformer corresponding to the antiperiplanar arrangement of all the C—C—C—C dihedrals and the Y—C—C—C, C—Y—C—C, and X—C—Y—C dihedrals, where the terminal CH₃ group in the n -octyl chain was in a skew conformation, were considered (1–18, Table I). The compounds with $X = CH_2R'$ (where $R' = H, CH_3$) were optimized from an eclipsed conformation of the O=C—C_X—R' unit. When $R' = CH_3$, this group was initially arranged in its skew form. The equivalent conformation was adopted as the starting point for the compounds with $X = OR$ and $X = NHR$ (with $R = H, CH_3$). The environment of the N atom in the systems that included it (6–7 and 10–18, Table I) was assumed to be planar for consistency with the results of previous experimental²⁷ and theoretical²⁸ conformational studies that confirmed the usefulness of the 6-31G* basis set for conformational analyses of these systems.¹⁷

The following bond properties were tabulated and analyzed: intermolecular distance (R); bond ellipticity, $\varepsilon = (\lambda_1/\lambda_2) - 1$, where $|\lambda_1| > |\lambda_2|$ are the two negative eigenvalues of the Hessian of the charge density at the critical point; charge density at the critical point, $\rho(r_c)$; Laplacian of the charge density at the critical point, $\nabla^2\rho(r_c)$; total energy density at the critical point $H(r_c)$ ^{29,30}; and ratio of the distance from atom A to the bond point and the A—B bond distance, $s(A-B)$. The tabulated

TABLE I.
Atomic Properties of O Atom and Bond Properties of C=O Bond (a.u.).

Mol	X	Y	O				C=O				
			Q	E_{at}	V_{neo}	v	R	s	ε	$\rho(r_c)$	$-\nabla^2\rho(r_c)$
1	H	O—Oct	−1.3919	−75.5828	−185.5211	112.55	1.1842	67.30	0.1086	0.4418	0.4755
2	Me	O—Oct	−1.4070	−75.5924	−185.6036	111.93	1.1885	67.31	0.1028	0.4388	0.4163
3	Et	O—Oct	−1.4089	−75.5913	−185.6167	111.50	1.1891	67.33	0.0946	0.4377	0.4266
4	OH	O—Oct	−1.4352	−75.6362	−185.8074	111.78	1.1896	67.21	0.1318	0.4452	0.1995
5	OMe	O—Oct	−1.4339	−75.6305	−185.8080	110.60	1.1900	67.23	0.1291	0.4437	0.2236
6	NH ₂	O—Oct	−1.4373	−75.6063	−185.7717	112.62	1.1946	67.20	0.1079	0.4399	0.1390
7	NHMe	O—Oct	−1.4383	−75.5965	−185.7673	112.35	1.1965	67.22	0.1037	0.4375	0.1467
8	F	O—Oct	−1.4021	−75.6685	−185.7321	110.34	1.1737	67.14	0.1858	0.4600	0.3671
9	Cl	O—Oct	−1.3844	−75.6124	−185.5700	109.87	1.1734	67.18	0.1399	0.4549	0.5209
10	H	NH—Oct	−1.4005	−75.5286	−185.4693	114.57	1.1963	67.30	0.0724	0.4309	0.3281
11	Me	NH—Oct	−1.4120	−75.5388	−185.5370	113.95	1.2007	67.33	0.0690	0.4278	0.2851
12	Et	NH—Oct	−1.4131	−75.5403	−185.5533	112.94	1.2012	67.34	0.0611	0.4265	0.3027
13	OH	NH—Oct	1.4408	−75.5986	−185.7642	113.60	1.1965	67.21	0.1055	0.4385	0.1187
14	OMe	NH—Oct	−1.4385	−75.5960	−185.7680	112.40	1.1965	67.22	0.1032	0.4374	0.1476
15	NH ₂	NH—Oct	−1.4386	−75.5647	−185.7070	114.06	1.2039	67.20	0.0814	0.4316	0.0424
16	NHMe	NH—Oct	−1.4385	−75.5579	−185.7054	113.32	1.2055	67.23	0.0772	0.4293	0.0583
17	F	NH—Oct	−1.4108	−75.6392	−185.7180	112.07	1.1786	67.13	0.1581	0.4551	0.2891
18	Cl	NH—Oct	−1.3914	−75.5831	−185.5529	111.44	1.1783	67.16	0.1102	0.4501	0.4341

atomic properties used were the charge (Q), the atomic energy (E_{at}), the potential energy of interaction of the nucleus of Ω with the atomic charge density (V_{neo}), and the atomic volume bounded by a surface of 0.002-a.u. charge density (v). The effect of substituent electronegativity was assessed by calculating the group electronegativity for X following Boyd et al.³¹ The electronegativity values thus obtained were directly related to the charges for the X substituent shown in Table III with the exception of the H atom, whose electronegativity was similar to that of Li or Na and hence significantly underestimated. For this reason, in what follows, all electronegativity relations are handled as a dependence on the charge of the X substituent.

Results and Discussion

C=O BOND

Tables I and II summarize the atomic and bond properties of the O and C atoms of the carbonyl group in each of the 18 molecules studied. As can be seen in Table I, C=O bond distances ranged from 1.1734 Å (9) to 1.2055 Å (16). A comparison of the values for compounds bearing the same X substituent reveals that the esters have C=O distances shorter than those of the amides. This in-

creased C=O bond length in amides has traditionally been ascribed to the lower π character of this bond resulting from a stronger involvement of the resonance structure containing a $\text{C}=\text{N}^+$ double bond and bearing a negative charge on the oxygen.³² This interpretation was shown to be inaccurate by Wiberg and Laidig on the basis of the atomic and bond properties of the planar conformer of formamide and the transition state of its internal rotation.¹⁷ The increased bond length in amides has also been found in experimental gas phase data.³³ Although the CO bond lengths are affected by the molecular environment, some general trends, also found for experimental gas phase data,³³ could be established. So, considering the $X=\text{H}$ compound as a reference value, bond length is scarcely affected by Me and Et X substituents, is increased by F and Cl, and decreased by NH_2 .

Because the π character of a bond can be quantified under the AIM theory via the ellipticity, ε , of the bond (the higher the ellipticity the more marked the π character), the data in Table I could be considered to favor the involvement of the resonance structure bearing a single $\text{O}^- - \text{C}=\text{Y}^+$ bond, because the ellipticity of the C=O bond in the amides (10–18) is smaller than in the esters (1–9). It should be noted, however, that the $\varepsilon(\text{C}=\text{O})$ values for esters 1–3 and amides 10–12 exceed those computed in previous work⁵ for the

TABLE II. Atomic Properties of C Atom and Bond Properties of C—X and C—Y Bonds (a.u.).

Mol	C				C—X					C—Y				
	<i>Q</i>	<i>E</i> _{at}	<i>V</i> _{neo}	<i>v</i>	<i>R</i>	<i>s</i>	<i>ε</i>	<i>ρ</i> (<i>r</i> _c)	−∇ ² <i>ρ</i> (<i>r</i> _c)	<i>R</i>	<i>s</i>	<i>ε</i>	<i>ρ</i> (<i>r</i> _c)	−∇ ² <i>ρ</i> (<i>r</i> _c)
1	2.0297	−36.4956	−81.2579	31.0	1.0853	63.76	0.0317	0.3081	1.2081	1.3150	31.87	0.0748	0.3212	0.0372
2	1.9035	−36.5659	−81.7469	28.0	1.5050	53.66	0.0639	0.2750	0.8141	1.3250	31.86	0.0969	0.3148	0.0797
3	1.8855	−36.5838	−81.8240	27.8	1.5103	54.00	0.0752	0.2736	0.8063	1.3252	31.85	0.1043	0.3143	0.0720
4	2.7398	−35.9839	−78.2226	14.6	1.3207	31.98	0.0025	0.3279	0.2808	1.3065	32.08	0.0181	0.3383	0.2606
5	2.7346	−35.9902	−78.2504	14.7	1.3142	32.07	0.0131	0.3323	0.2765	1.3113	32.07	0.0161	0.3345	0.2679
6	2.6260	−36.0950	−78.8124	16.1	1.3485	33.30	0.1063	0.3440	1.0725	1.3271	32.00	0.0368	0.3194	0.2414
7	2.6046	−36.1136	−78.9133	16.7	1.3456	33.43	0.1319	0.3484	1.1082	1.3295	32.00	0.0383	0.3172	0.2363
8	2.7843	−35.9285	−77.9622	14.2	1.3042	32.14	0.0998	0.2878	−0.3280	1.2986	32.17	0.0733	0.3474	0.3048
9	2.2149	−36.2910	−80.3765	24.1	1.7462	43.28	0.0649	0.2127	0.4134	1.3022	32.15	0.0233	0.3407	0.2278
10	1.9578	−36.5604	−81.6473	31.5	1.0916	62.63	0.0223	0.3002	1.2095	1.3440	32.71	0.0393	0.3379	0.7907
11	1.8567	−36.6208	−82.0592	28.2	1.5156	52.21	0.0461	0.2695	0.7725	1.3519	32.80	0.0265	0.3338	0.8297
12	1.8382	−36.6364	−82.1332	28.3	1.5217	52.54	0.0569	0.2681	0.7641	1.3520	32.80	0.0202	0.3336	0.8264
13	2.6024	−36.1061	−78.9088	16.8	1.3365	31.92	0.0555	0.3125	0.2386	1.3403	33.42	0.1386	0.3523	1.1118
14	2.6076	−36.1130	−78.9054	16.4	1.3317	32.00	0.0403	0.3158	0.2453	1.3441	33.43	0.1354	0.3496	1.1095
15	2.5112	−36.1970	−79.3956	17.6	1.3631	33.22	0.0490	0.3293	0.9856	1.3572	33.33	0.0780	0.3366	1.0314
16	2.4939	−36.2121	−79.4782	17.9	1.3608	33.35	0.0724	0.3338	1.0270	1.3595	33.34	0.0744	0.3347	1.0250
17	2.6461	−36.0666	−78.6755	16.6	1.3251	32.11	0.1693	0.2693	−0.3068	1.3348	33.65	0.2020	0.3590	1.1885
18	2.1299	−36.3799	−80.8333	25.6	1.7803	42.45	0.0418	0.1948	0.3377	1.3341	33.61	0.1570	0.3549	1.0995

corresponding ketones or aldehydes—where such resonance forms could never occur, viz., 0.0677 for *n*-decanal, 0.0589 for 2-undecanone, and 0.0496 for

TABLE III. Atomic Properties of X Group (a.u.)^a

Mol	X			
	<i>Q</i>	<i>E</i> _{at}	<i>V</i> _{neo}	<i>v</i>
1	0.0205	−0.6314	−1.2859	35.0
2	0.1731	−39.6249	−92.9973	169.2
3	0.1890	−78.6634	−184.8415	299.0
4	−0.6605	−75.8654	−186.1708	112.5
5	−0.6511	−114.9332	−276.5550	244.4
6	−0.5242	−56.0276	−137.3962	141.4
7	−0.5034	−95.0806	−228.0199	271.2
8	−0.7486	−99.8336	−243.6520	85.6
9	−0.2027	−459.8024	−1097.2820	167.8
10	−0.0529	−0.0193	−0.0408	2.3
11	−0.0805	−0.0223	−0.1381	2.9
12	−0.0751	−0.0197	−0.1050	2.5
13	−0.0131	0.0280	−0.0014	1.0
14	−0.0250	0.0388	0.0180	2.9
15	−0.0217	0.0217	0.0719	1.5
16	−0.0230	0.0270	0.1027	1.5
17	−0.0091	0.0350	0.0146	1.2
18	−0.0767	0.0082	−0.4790	5.5

^a The values for amides are relative to those for the corresponding esters.

3-dodecanone. On the other hand, the ellipticities of the C—Y bonds in amides 10–12 (Table II) are lower than those in the corresponding esters (1–3), consistent with the results of Bader and Chang for the C—N and C—O bonds in aniline and phenol, respectively,²⁰ and ruling out an increased involvement of the aforementioned resonance structure in the nitrogen-containing compounds.

The difference in C=O distance between amides and esters decreases with increase in the electronegativity of X. This can be explained based on the larger effect of X on the electronic charge density at Y, which reduces the differential effect of N and O at position Y. Thus, such a difference is maximal (0.012 Å) for alkyl groups (X = H, Me, Et), lower for nitrogen- (0.010 Å) and oxygen-containing compounds (0.007 Å), and minimal (0.005 Å) for halogen-containing compounds (X = F, Cl).

If the C=O bond distance for a ketone bonded to a long-enough alkyl chain (e.g., in undecanone, for which 6-31G*-optimized computations provided a distance of 1.193 Å) is adopted as a reference value, then the C=O distance increases only in those amides containing no halogens, the lengthening being maximal in the diamides (viz., ureas 15 and 16, with 0.011 and 0.013 Å, respectively). On the other hand, the greatest shortening in the C=O bond distance is observed in the halogen-containing compounds (−0.036 Å in the diflu-

orinated derivative).¹⁷ The differences introduced in this behavior by the presence of an F or Cl atom are negligible (< 0.001 Å). Unless the molecule also contains a nitrogen atom, the presence of an oxygen atom such as X or Y causes a slight shortening of the bond (from 0.011 Å in formic acid¹⁷ to 0.003 Å in octyl carbonate, 4) not always exceeding that produced by a combination of alkyl groups. No quantitative correlation between C=O bond distance and electronegativity of X and Y substituents was found.

The position of the C=O bond critical point does not change markedly among compounds when those bearing X and Y substituents of considerably different electronegativity are excluded. Thus, for a given X group, differences between esters and amides are minimal. Only those compounds having a halogen atom as X exhibit appreciable differences from those where X is an alkyl group the latter displaying a significant approach of the bond critical point to the oxygen atom. This tendency, which is observed in both esters and amides, suggests that the oxygen atom is slightly more electronegative and can be analyzed in quantitative terms via the correlation between quantity s and the charge of the X substituent, $Q(X)$. Such a correlation is initially low but increases substantially ($r^2 = 0.87$) if chlorine-containing compounds are excluded. These findings are a departure from the behavior of the other derivatives, in which all the substituents belong to the first row of the periodic table.

Because AIM theory uses ε to quantify the double character of a bond, we correlated it with the internuclear distance, R (see Fig. 1 of Supplementary material [SM]). As expected, ε increased with decreasing R ; however, the compounds studied exhibited three different types of behavior that allow one to establish a preliminary classification of the X substituent. This differential behavior is reflected in the two fitted lines of Figure 1 and in the pattern of the chlorinated derivatives, inclusion of which in either series significantly decreases its r^2 coefficient. The points in the upper line ($r^2 = 0.989$) correspond to the ten molecules bearing the most electronegative substituents ($X = \text{OH, OMe, NH}_2, \text{NHMe, and F}$; i.e., series I), whereas those in the lower line ($r^2 = 0.96$) correspond to the six compounds with the least electronegative ones ($X = \text{H, Me, and Et}$; i.e., series II). Although the ε/R ratio is similar for both series, the magnitude of the variation is slightly greater in the former, as can be inferred from the greater slope of its line in Figure 1 (SM). The

differences in ε are significant: in both esters and amides, the largest ε value corresponds to the molecule with $X = \text{F}$ and the smallest to that with $X = \text{Et}$; also, the largest ε is twice as high as the second in the ester series and more than two times higher in the amide series. In qualitative terms, these differences can be ascribed to the σ -withdrawing and π -donating abilities of the X groups: OR, NHR, and F.²⁰ It has been shown previously that σ -withdrawing ability increases and the π -donating ability decreases in this order. So, F produces a faster reduction of the charge density when moving apart the C=O bond path inside the σ plane, increasing the λ_1 curvature. On the other hand, F, as a slight π donor, produces a small increase in the electron charge density in the π plane, leading to a small decrease of λ_2 . Both effects are reflected by a meaningful increase of $\varepsilon(\text{C=O})$. For the same reason, ε is always lower in amides than in the corresponding ester (OR substituents display larger σ -acceptor and lower π -donor abilities than NHR groups). The π -donor and σ -donor groups (H, Me, Et) exhibit decreases in both λ_1 and λ_2 absolute values, yielding the lowest ε values in the compounds studied here.

The $\rho(r_c)$ value is often recognized as a number highly correlated with the bond order. The ρ/R representation should reflect in a line of negative slope because the bond order increases with increasing critical-point density. Figure 2 (SM) shows the actual relationship found. The correlation coefficient was $r^2 = 0.996$ for series I and $r^2 = 0.998$ for series II. Although their position in the graph might suggest it, the values for Cl are again uncorrelated to series II, which includes π donors.²⁰ The differences in ρ are much less significant than those in ε , giving rise to much less marked variations of this magnitude with the electronegativity of the X and Y substituents.

Although the value of the Laplacian of the charge density at the critical point, $\nabla^2\rho(r_c)$, has normally been used to indicate the ionic [$-\nabla^2\rho(r_c) < 0$] or covalent [$-\nabla^2\rho(r_c) > 0$] character of the bond, it has been found that this magnitude cannot be interpreted in these terms for a C=O bond because of the nearness of the bond critical point to a nodal surface of $\nabla^2\rho$. In these cases, the atomic basins neighboring the interatomic surface exhibit opposite behavior with respect to the sign of the $\nabla^2\rho$ (Table I) as was previously found.^{2,34,35} Cremer and Kraka found that a pointwise analysis of kinetic energy density, $G(r)$, and potential energy density, $V(r)$, indicates that for covalent bonds the

local energy density, $H(r) = G(r) + V(r)$, at sites of maximum concentration of $\rho(r)$, is always negative.^{29,30} Thus, negative values of $H(r_c)$, such as those of every C=O bond considered in this work, suggest a local concentration of charge in the internuclear zone typical of covalent bonds. Figure 3 (SM) shows the relationship between $H(r_c)$ and the bond distance, R . The two series of aligned data in Figure 3 accurately match the series observed in the previous figures. This relationship suggests that charge concentration is more marked in the shorter bonds. On equal X substituents, the covalent character of the C=O bond is greater in the esters than in the amides, and minimal in the two ureas studied (15, 16).

To quantify the dependence of bond properties on substituent electronegativity, potential relationships between the charge of X , $Q(X)$, ε , and $\rho(r_c)$ were sought. The relationships found were qualitatively poor but allowed us to distinguish four types of molecules belonging to the aforementioned series I and II that also provided a distinction between amides and esters.

Figure 4 (SM) shows the variation of the charges on O, C, and C=O with $Q(X)$. Figure 4, which shows relative values of the charges, reveals that the variation of the total charge of the C=O group arises mainly from the variation undergone by the carbon bonded to the substituent. The charge of the oxygen atom remains virtually constant relative to that on the carbon. The correlation between the charges on C or C=O and those on the substituents is excellent ($r^2 \geq 0.988$) if esters and amides are considered separately. The positive charge of the carbon, and hence that of the carbonyl group, increases with an increase in the negative charge of X . In fact, the C atom and the C=O group are always more positive in the amides than in the esters because the oxygen at Y in the latter possesses a more negative charge than does N in the amides.

The energy quantities studied in this work, viz., E_{at} and V_{neo} , exhibit marked differences among the C=O groups in the compounds studied. Thus, the average difference in E_{at} for the oxygen atom between amides and esters is 108 kJ/mol, and its maximum value 142 kJ/mol (with $X = H$). The electronegativity of the substituent, expressed as a function of its charge, is uncorrelated to the energy (E_{at} or V_{neo}) of the oxygen atom; however, the energy (E_{at} and V_{neo}) of the carbonyl group, expressed as the summation of the values for C and O, is very highly correlated with the charge of the X substituent (Figs. 5 and 6 SM), even though the

energy differences are very large. Thus, the differences in V_{neo} are about 4 a.u. (i.e., $> 10^3$ kJ/mol). On the other hand, the E_{at} and V_{neo} values for the oxygen atom exhibit a disparate behavior. Thus, E_{at} is less easily related in qualitative terms to the substituent electronegativity: F-containing esters exhibit lower values than do amides with $X = H$. On the other hand, V_{neo} is lower for molecules with $X = OR$ and NHR than in those with $X = F$.

The volume of the C atom and the charge of the X substituent are slightly correlated; however, this correlation, improves when molecules with $X = H$ are excluded ($r^2 = 0.886$ for the 18 molecules as a whole and $r^2 = 0.92$ when 1 and 10 are excluded). There is also some correlation between the volume of the carbon atom and the C— X bond distance (Fig. 7 SM). If we exclude the molecules with $X = Cl$ and H , whose C— X bonds are markedly different from those in the rest and include the longest and shortest of all, then the resulting correlation is excellent ($r^2 = 0.991$). Thus, the larger the atomic volume the longer the bonds. Consequently, the C atom possesses a greater volume in the amides than in the esters because the C—N distance is longer than the C—O distance.

C—X BOND

Table II summarizes the properties of the C— X bonds and Table III shows the atomic properties of the X substituent computed by adding the individual values obtained for every atom of this group. As noted earlier, the charge of the X substituent has been related to its electronegativity and was used in this work to derive qualitative relationships for the dependence on this property. In fact, there were two differential behaviors from the compounds with $X = F$, NH_2 , OH , $NHMe$, OMe , and Cl (i.e., substituents with negative charge and a high electronegativity), on the one hand, and those with $X = H$, Me , and Et (with positive charge and a low electronegativity) on the other. Figure 8 (SM) shows the relationship between the charge of the X substituent and the position of the C— X bond critical point, expressed as s . If the molecules with $X = H$ are excluded, then the correlation is excellent ($r^2 = 0.97$). In such molecules (1–10), the critical point is very close to the substituent atom by virtue of its small size. This relationship is based in the fact that s values can also be related to electronegativity because the bond critical point is closer to the more electronegative atoms. Slee et al.³⁶ found a similar relationship for ethyl and formyl derivatives with $X = F$,

OH, NH₂, CN, HCH=CH₂, and CH₃. According to Slee and coworkers, charge transfer in these bonds is governed by the electronegativity of the substituent rather than by its π -electron-releasing or -withdrawing character, which has a weaker influence on the position of the bond critical point.

C—X bonds differ widely in nature, so direct comparisons of their properties are elusive. Ellipticity is higher for amides in some cases and for esters in others. With bonds of the same type (e.g., C—N), the difference in ε introduced by the presence of an amide or ester function in Y (about 0.06) is much greater than that introduced by the X substituent itself (< 0.03). As a rule, the differences observed cannot be related to substituent properties, not even in qualitative terms, so they must be the result of several combined factors. Similar, although less marked, differences are observed in $\rho(r_c)$ that exclude relationships with the substituent properties. The most significant difference is that in $-\nabla^2(r_c)$ for the C—F bond, which, unlike the rest, has a negative value consistent with its highest polarity along the 18 samples. However, $H(r_c)$ values are consistent with covalent character for every C—X bond.

Regarding differences in the integrated properties of X in the series, because the atoms are so widely dissimilar in nature, they exhibit marked differences (e.g., the energy for the Cl atom is nearly 5 times higher than that of F and 700 times higher than that of H)—differences that can be ascribed to such obvious effects as an increased number of electrons or a substantially different electronegativity. We thus considered it useful to examine only changes in the properties of the X substituent between amides and esters. The effects of replacing the ester group with the amide group can be summarized as follows:

1. There is an increased electron population with a more negative charge, an effect that is much more marked in an alkyl substituent than in a highly electronegative one such as F, the charge of which changes by less than 0.01 a.u.
2. There is an increased atomic volume that is especially significant in absolute terms in the Cl atom and in relative terms in the H atom (> 6%).
3. There is an increased electronic kinetic energy in those substituents that exhibit the most substantial increase in electron population (viz., H, Me, and Et) and a decreased

value in the others. It should be noted that, despite its markedly increased electron population in the amide environment, the Cl atom possesses a slightly decreased energy in it as the likely result of the increased distance between the electrons and the nucleus.

4. The attraction of the electronic charge of the fragment by the nucleus is maximal, in absolute terms, in the compounds with the most markedly increased electron populations and smaller in the rest.

C—Y BOND

Closeness to the C—X bond influences the atomic properties of the atom or atoms at position Y (Table IV), resulting in considerable differences in the charge $Q(Y)$ among the molecules (0.0217 for esters and 0.0447 for amides); also, it can be correlated with the charge of the X substituent if the two series considered in the previous sections are distinguished. Although the charge of N is always smaller than that on O, their combination with those on H results in the increased values shown in Table IV. In every case, the Y substituent exhibits a decreased electron population in the halogen-containing derivatives particularly in the amides, as one would expect from qualitative considerations based on inductive effects.

TABLE IV.
Atomic Properties of Y Group (a.u.).

Mol	Y			
	Q	E_{at}	V_{neo}	v
1	-1.3573	-75.6001	-185.7324	88.9
2	-1.3686	-75.5970	-185.7748	89.0
3	-1.3647	-75.5956	-185.7662	88.4
4	-1.3604	-75.6471	-185.8364	87.2
5	-1.3567	-75.6360	-185.8098	86.9
6	-1.3650	-75.6137	-185.8078	87.7
7	-1.3656	-75.6057	-185.8001	87.6
8	-1.3530	-75.6599	-185.8300	86.6
9	-1.3469	-75.5967	-185.7060	86.7
10	-1.1251	-55.7443	-136.9564	111.5
11	-1.1302	-55.7420	-136.9591	111.3
12	-1.1310	-55.7411	-136.9617	111.2
13	-1.1113	-55.7642	-137.0440	110.0
14	-1.1072	-55.7569	-137.0175	109.2
15	-1.1246	-55.7380	-136.9839	110.8
16	-1.1252	-55.7318	-136.9274	110.7
17	-1.0948	-55.7654	-137.0226	108.9
18	-1.0863	-55.7193	-136.9319	109.7

The atomic energy, E_{at} , increases with decreasing charge on the substituent; on the other hand, V_{neo} and atomic volumes exhibit no clear-cut relationship. The kinetic and potential energies are always higher for the NH group. Also, atomic volumes are higher for N than for O, and are further increased when the volume of the bonded H atom is added.

The C—Y bond critical point is closer to the N atom in the amides than it is to the C atom in the esters; also, the electronegativity of the O atom in the esters is higher than that of the N atom in the amides. Within each series, the C—Y bond distance is quantitatively related to the charge of the X substituent (see Fig. 9, SM). The r^2 values are again > 0.97 if series I is split into two, encompassing the amides and the esters, respectively. No r^2 values were computed for the molecules in series II as the number of points available was deemed inadequate. No similar correlation for ε exists; this parameter exhibits large relative variations. The substituent charge has a stronger influence on the $\rho(r_c)$ and $-\nabla^2\rho(r_c)$ values. The

Laplacian is highly correlated with $Q(X)$; the correlation does not distinguish between series I and II, although the chloride-containing molecules depart slightly from the others in this respect. Both $-\nabla^2\rho(r_c)$ and $H(r_c)$ indicate a covalent character for every C—Y bond. It is worth noting the increased covalent character of the C—Y bond in the amides. The magnitude of this variation is especially large for $-\nabla^2(r_c)$ values compared with the behavior exhibited by $H(r_c)$.

METHYLENE GROUPS

Tables V and VI (SM) and Table VII show the charges, energies, and s values for methylenes and the methyl group in the n -octyl chain present in all molecules, in addition to RMS values and the largest differences for the ester and amide series. Tabulated values allow one to determine the influence of the substituent on the properties of the chain by comparing the property concerned in adjacent methylenes within a molecule or methylenes at the same position in different molecules.

TABLE VII.
 s -Values for C—Y $s(M_i)$ and C—C Bonds in n -Octyl Chain.^a

Mol	$s(M_1)$	$s(M_2)$	$s(M_3)$	$s(M_4)$	$s(M_5)$	$s(M_6)$	$s(M_7)$	$s(M_8)$
1	0.6865	0.5212	0.5050	0.5040	0.5020	0.5012	0.5009	0.4978
2	0.6863	0.5193	0.5043	0.5034	0.5016	0.5010	0.5007	0.4977
3	0.6862	0.5191	0.5041	0.5033	0.5016	0.5009	0.5007	0.4977
4	0.6876	0.5229	0.5052	0.5043	0.5020	0.5013	0.5008	0.4979
5	0.6870	0.5191	0.5044	0.5033	0.5016	0.5009	0.5007	0.4977
6	0.6873	0.5216	0.5045	0.5038	0.5017	0.5011	0.5007	0.4977
7	0.6868	0.5184	0.5040	0.5031	0.5015	0.5008	0.5006	0.4976
8	0.6882	0.5262	0.5071	0.5055	0.5028	0.5019	0.5012	0.4981
9	0.6875	0.5264	0.5070	0.5055	0.5028	0.5019	0.5012	0.4981
M	0.6870	0.5216	0.5051	0.5040	0.5020	0.5012	0.5008	0.4978
RMS	0.0006	0.0030	0.0012	0.0009	0.0005	0.0004	0.0002	0.0002
MD	0.0020	0.0080	0.0031	0.0024	0.0013	0.0011	0.0006	0.0005
10	0.6726	0.5111	0.5070	0.5032	0.5022	0.5011	0.5010	0.4978
11	0.6719	0.5095	0.5063	0.5026	0.5019	0.5009	0.5008	0.4977
12	0.6715	0.5094	0.5061	0.5025	0.5018	0.5009	0.5008	0.4977
13	0.6745	0.5122	0.5069	0.5033	0.5021	0.5012	0.5009	0.4978
14	0.6736	0.5112	0.5063	0.5029	0.5019	0.5010	0.5008	0.4977
15	0.6731	0.5091	0.5062	0.5024	0.5018	0.5008	0.5008	0.4976
16	0.6725	0.5086	0.5059	0.5022	0.5017	0.5007	0.5007	0.4976
17	0.6759	0.5149	0.5085	0.5044	0.5029	0.5017	0.5013	0.4981
18	0.6751	0.5154	0.5088	0.5046	0.5030	0.5018	0.5013	0.4981
M	0.6734	0.5113	0.5069	0.5031	0.5021	0.5011	0.5009	0.4978
RMS	0.0015	0.0025	0.0011	0.0009	0.0005	0.0004	0.0002	0.0002
MD	0.0044	0.0068	0.0029	0.0024	0.0013	0.0011	0.0006	0.0005

^a M, mean; RMS, root mean square; MD, maximum differences.

In addition to the effect of functionalization, one must also consider the position relative to the terminal methyl group and the reliability with which the integrated property was computed. The latter is usually dictated by the precision attained in the zero-flux surface determination, which, for an atom, is assessed from $L(\Omega)$. For atom groups, that precision was estimated by the calculated value of the central atom, whose $L(\Omega)$ value usually exceeds those for the terminal groups by more than one order of magnitude.

As can be seen in Table V, the charge of the methylene groups (referred to as M_i where i indicates the number of bonds from Y group) decreases as they depart from the carbonyl unit; by exception. M_4 exhibits a slightly increased charge relative to M_3 and the methylene in α with respect to the terminal methyl (M_7) must exhibit a disparate behavior based on previous results.⁷ The RMS values for the esters exceed those for the amides. On the basis of the methylene or methyl similarity criterion of Wiberg et al.,⁷ which admits maximal differences of 0.001 in group charges, the influence of the substituent in the molecules studied is spread throughout the chain. This is confirmed by a comparison of the hydrocarbon charges obtained by Wiberg et al. (viz. 0.000 for methylene groups bonded to methylenes alone, 0.016 for methylenes bonded to a methylene and a methyl group, and 0.0165 for methyl groups). In this work, the effect of the precision with which the integrated properties were calculated on the values of such properties was considered and the correlations shown in Figure 10 were found. As can be seen, oscillations in the electronic charge on the fourth and higher methylenes (i.e., M_i , with $i > 3$) are directly related to $L(C_i)$ rather than to the effect of the X and Y substituents; in any case, the charge difference between these methylenes and that of an alkane can be ascribed to the presence of a carbonyl group in the molecule. It is worth noting that the greatest differences between the charges of methylenes 5 and 6 are comparable to the maximum charge values, consistent with a character roughly equivalent to that of a methylene group in an alkane. The methylene at position γ ($i = 3$) gives disparate regression lines for amides and esters, which suggests that this group has a different character for amide and ester series but independent of the X substituent in any case. The methylene in β gives rise to two series that encompass the esters and the amides, respectively, series where the charges are not directly related to $L(C_2)$. Therefore, the effect of the X substituent

must concentrate on the methylenes in α and β with respect to the Y group. Thus, the NH_2 and $NHMe$ X substituents are those most markedly affecting the group in α and also the least strongly influencing it in β . On the other hand, the methylenes in α and β have less and more positive charges, respectively, in the compounds where $X = F$ or Cl . This can be ascribed to the increased electronegativity of the X substituent facilitating the removal of charge from the more distant groups.

The Y substituent also affects the charge of the methylene groups; the α and β methylenes are more positive in the esters than in the amides; however, the latter exhibit a stronger effect on γ methylenes, the charges of which are even higher than those of β methylenes in some compounds (11, 12, 15, 16).

Table VI shows the energies for the molecules studied. None of the differences among molecules are comparable to those obtained by Wiberg et al. for hydrocarbons, which peaked at 2.5 kJ/mol. In fact, the differences found in this work were approximately 65 kJ/mol for all methylenes and the methyl group (M_8 in Tables V–VII), with the exception of methylene at position α in the esters, which exhibited even greater differences. The energies of the α and β methylenes were more negative in the amides than in the esters. The opposite was true for Me_i with $i \geq 3$, although δ methylene ($i = 4$) was an exception in some respects. The energy differences between methylenes corresponding to ester or amide molecules bearing different X substituents were independent of the position of the methylene group, with the possible exception of the α group in the esters. This provides evidence that the nature of this X substituent scarcely affects the energy of the methylene groups. The energy differences resulting from replacement of the ester by the amide function in molecules bearing the same X group are more marked at position α . Consequently, the substantial energy differences between α methylenes and the others can essentially be ascribed to the character of the Y group.

The position of (3, -1) critical points in the n -octyl chain, reflected in the s values of Table VII, shows that the character of the C atoms in α and β with respect to the Y group is dictated basically by that of the Y group, which distinguishes esters from amides. Thus, the esters exhibit more symmetry in the splitting of $Y-C_\alpha$ and $C_\alpha-C_\beta$ bonds. The X group can be considered the origin of the variations of s in series 1–9 and 10–18, the

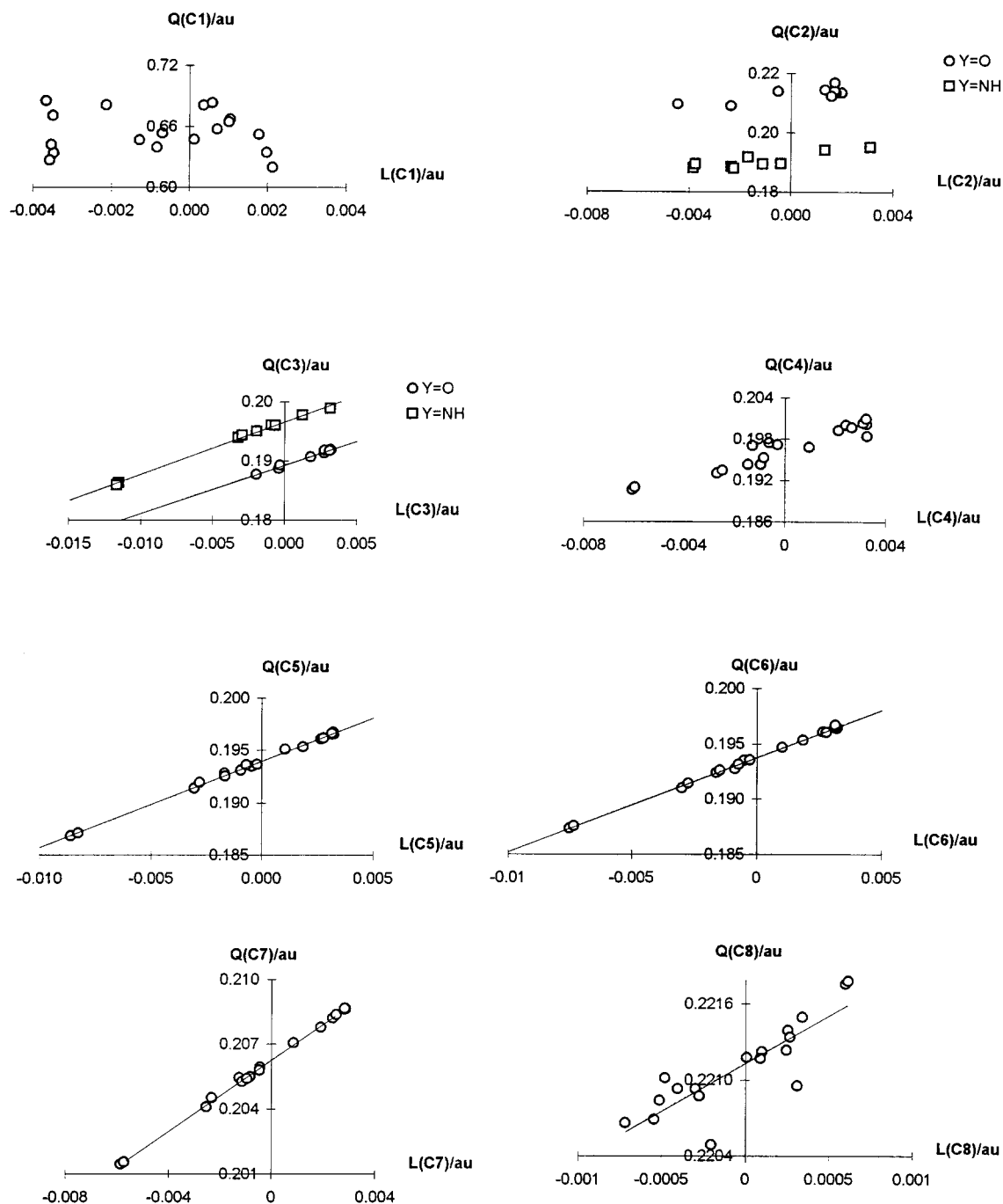


FIGURE 10. Plot of the charge of the C atoms of the n -octyl vs. the Laplacian of the charge density for the atom.

RMS and variation range of which decrease dramatically for the $C_\beta-C_\gamma$ and subsequent bonds in relation to the previous ones. The $C_\beta-C_\gamma$ bond exhibits a smaller though still significant asymmetry, particularly on account of the differences between s values in amides (0.5069) and esters (0.5051). This is consistent with previous conclu-

sions regarding the integrated properties, and supported the dependence of the methylenes in α and β with respect to Y on the character of both X and Y . The s value for the $C_\gamma-C_\delta$ bond can be assumed to converge for both series; δ methylene possesses similar properties in the esters and amides, which, however, are still different from

those in an alkane. In subsequent bonds, the average values of s virtually coincide and reflect minimal asymmetries that are quite consistent with those in an alkane.

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